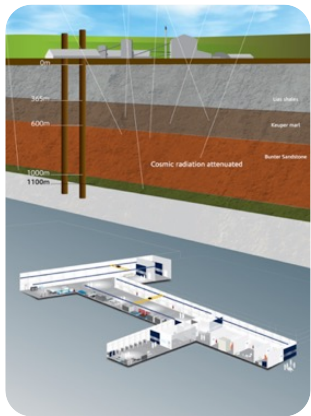


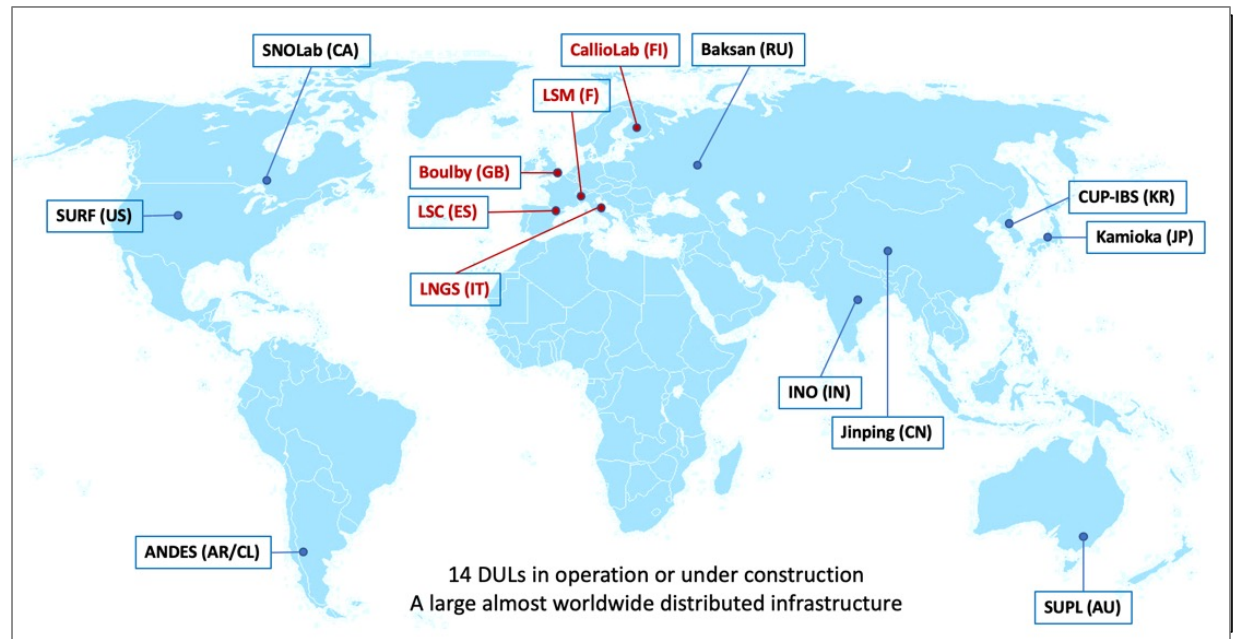
Overview of European Deep Underground Science Facilities



Boulby Underground Laboratory (UK)



LNGS (Italy)



Sean Paling
STFC Boulby Underground Laboratory

Why go underground?

Deep Underground Science Themes

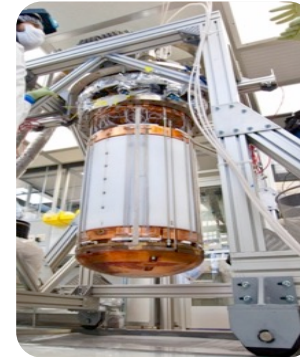
Low Background Particle / Astroparticle Physics

- Atmospheric, solar & supernova neutrinos
- Reactor and accelerator neutrinos
- Neutrino-less double beta decay
- Direct dark matter searches
- Nuclear astrophysics / stellar reactions
- Misc. rare-decay processes

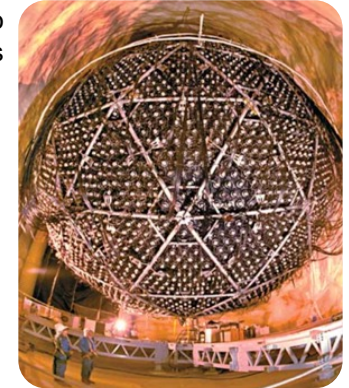
Other 'Multi-disciplinary' studies

- Cosmic rays studies
- ULB Gamma counting & spectroscopy
- Misc. Geology/geophysics
- Geo-microbiology & life in extreme environs
- Astrobiology
- Etc...

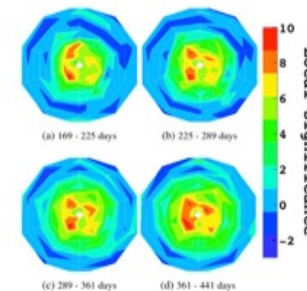
Dark
Matter
search



Neutrino
Studies



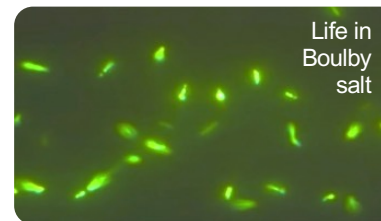
Geology &
geophysics



ULB Gamma
spectroscopy



Geo and
astrobiology



Life in
Boulby
salt

What's needed from an underground lab? (1)

Low Backgrounds...

Cosmic ray Muons...

- Deep underground facilities provide rock overburden & commensurate reduction in c.r. flux & spallation induced products (neutrons)

Neutrons...

Production from

- c.r. muon spallation
- U/Th fission
- α , n reactions

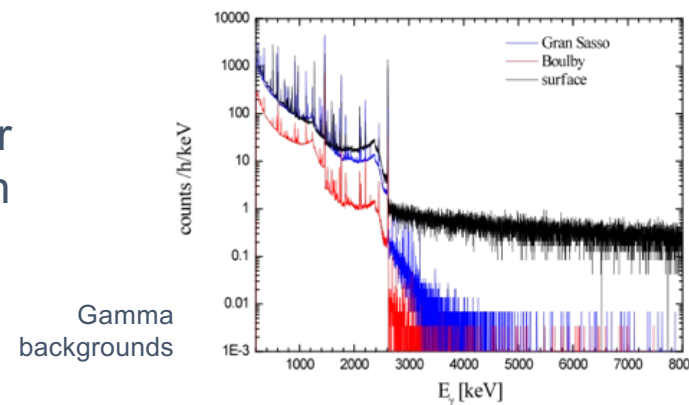
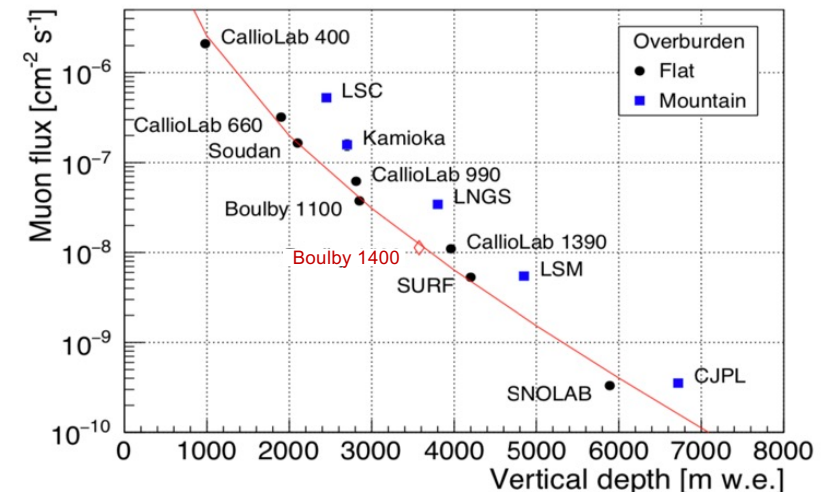
Radon....

- Dependent on local geology & ventilation

Gammas....

- Reduction in γ -ray background at higher energies from c.r. and neutron reduction
- Below 3.5MeV dependent on local geology

Muon Flux vs. Depth



What's needed from an underground lab? (2)

Other Factors:

Science and operations support:

- Good surface & underground infrastructure & support facilities
- Reliable utilities: power, ventilation, heat management, water, gases/liquids
- Good Health & Safety and security systems for underground use
- Scientific support personnel: design, construction, operation/analysis
- Infrastructure support and personnel: workshops, chemical labs, IT etc.
- Good ancillary science support facilities: low background assay, clean rooms etc...

**‘A hole in the ground
is not a facility!’**



Other Facility Characteristics:

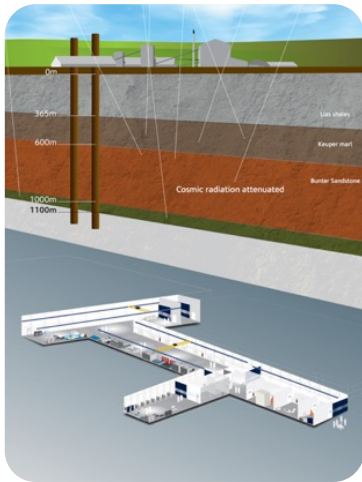
- Size (monolithic or distributed; Space available)
- Ease of Access (vertical or horizontal); Max installation size limitations
- Location (neutrino flux from beam/reactor, Earth, ease of access, quality of life)
- Cleanliness and radiological interference
- Suitable geology

**Non-infrastructure things are
very important too.**

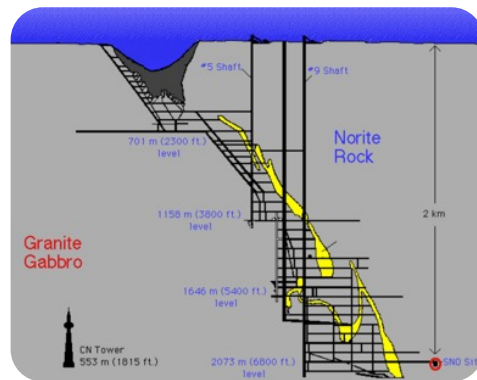


Local Politics & funding: multi-year budgets, solid host nation support, local support /engagement in the facility and the science. Science community networking.

Underground Labs around the world....

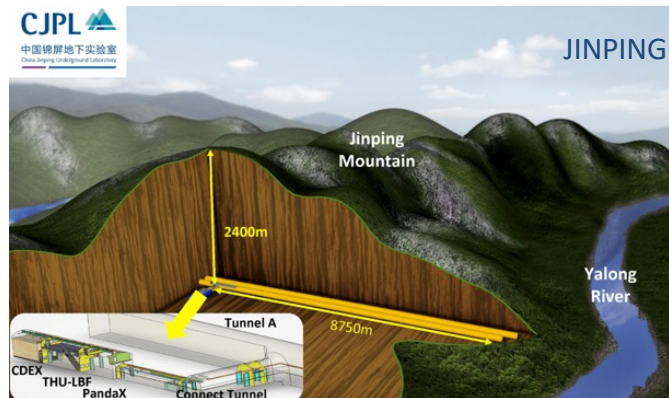


Boulby

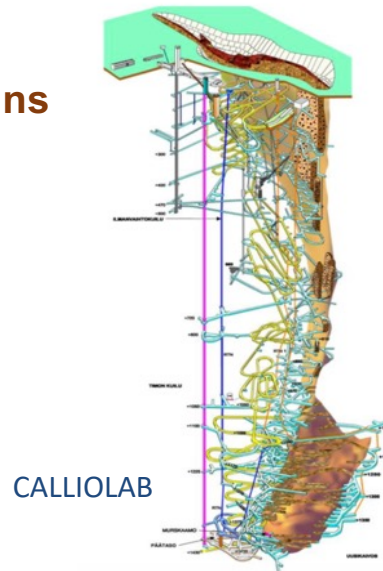


SNOLAB

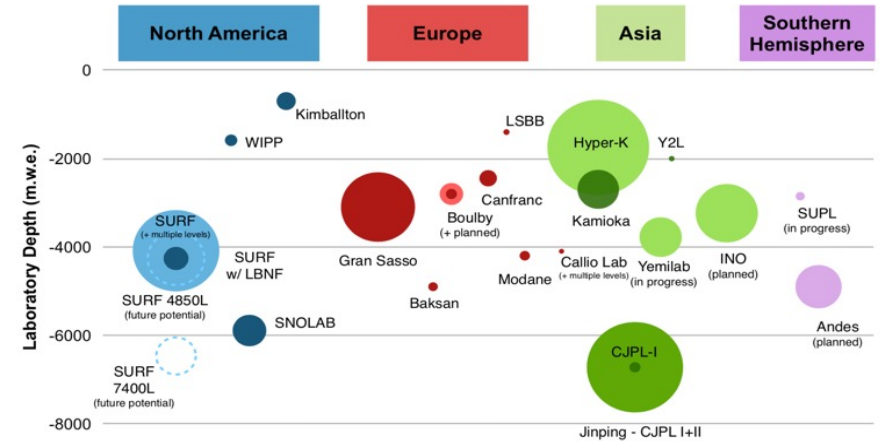
In mines and
under mountains



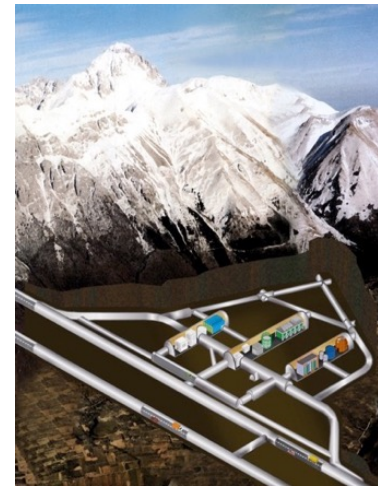
JINPING



CALLIOLAB

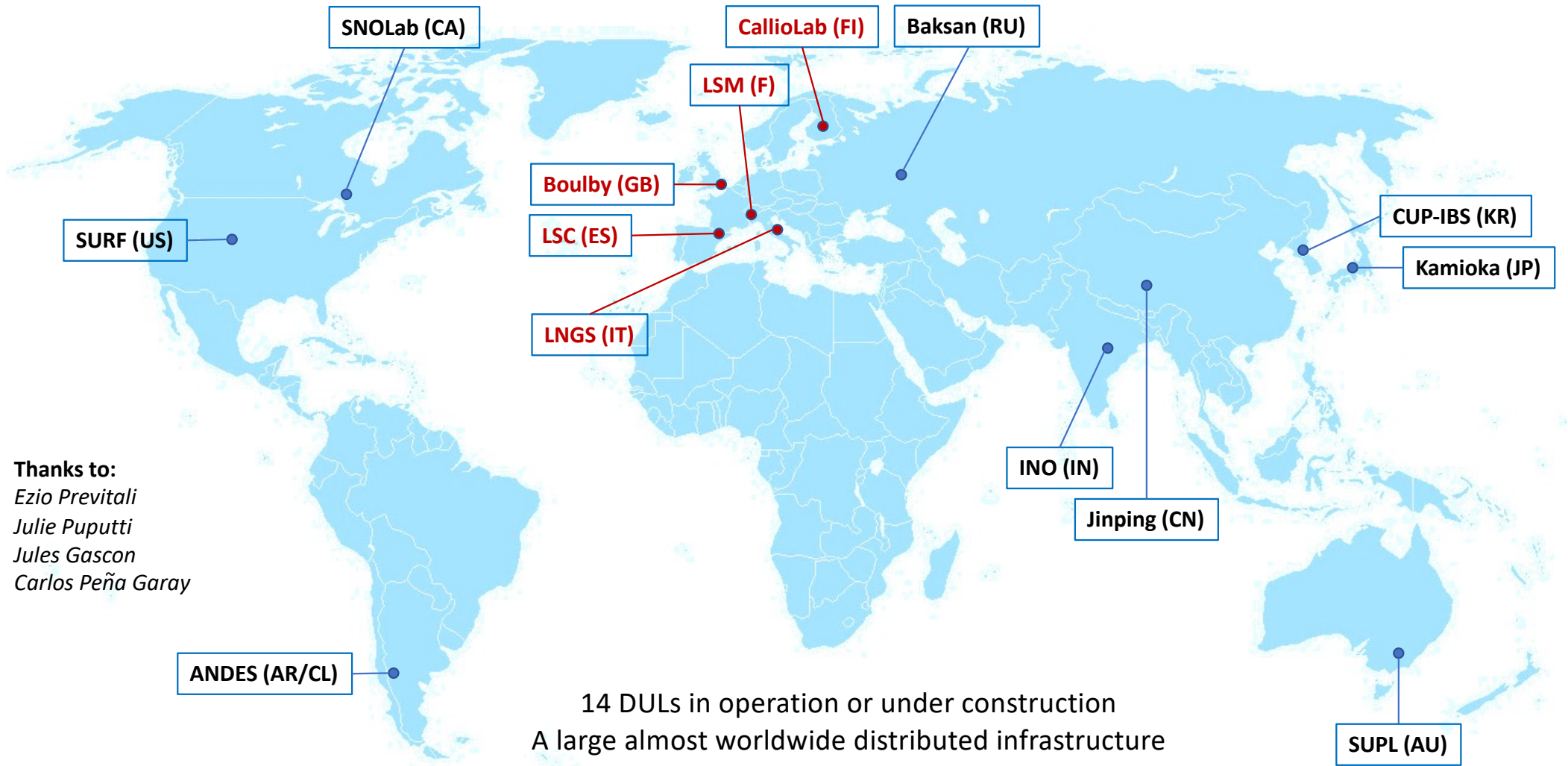


LNGS



SURF

World Deep Underground Science Labs



Thanks to:

Ezio Previtali

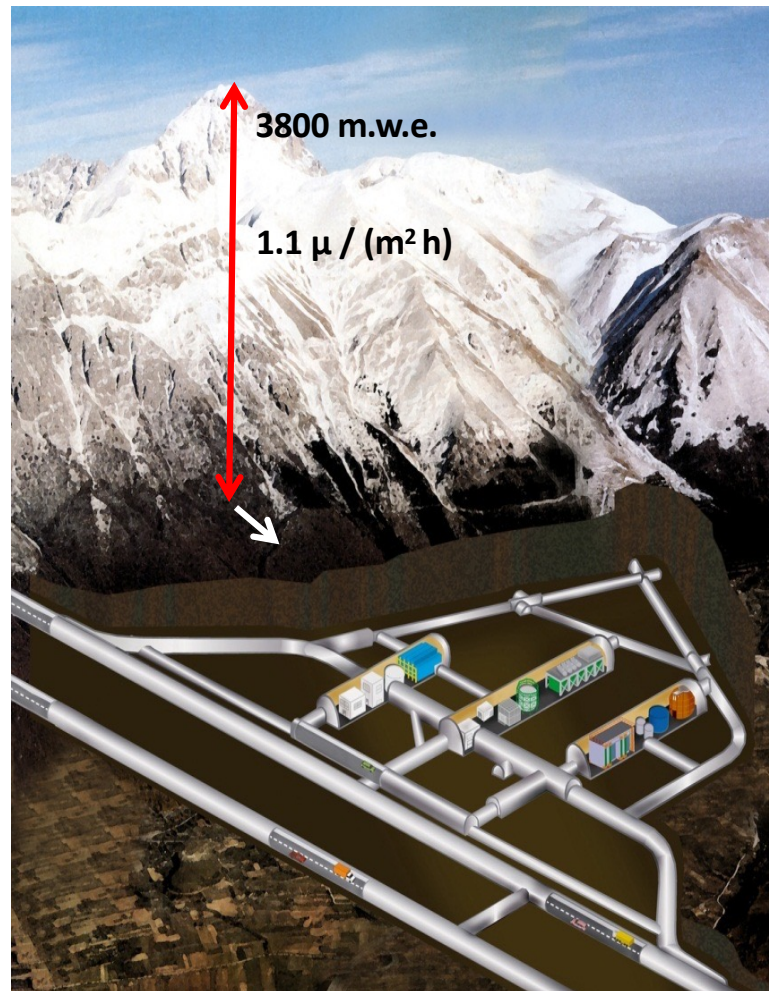
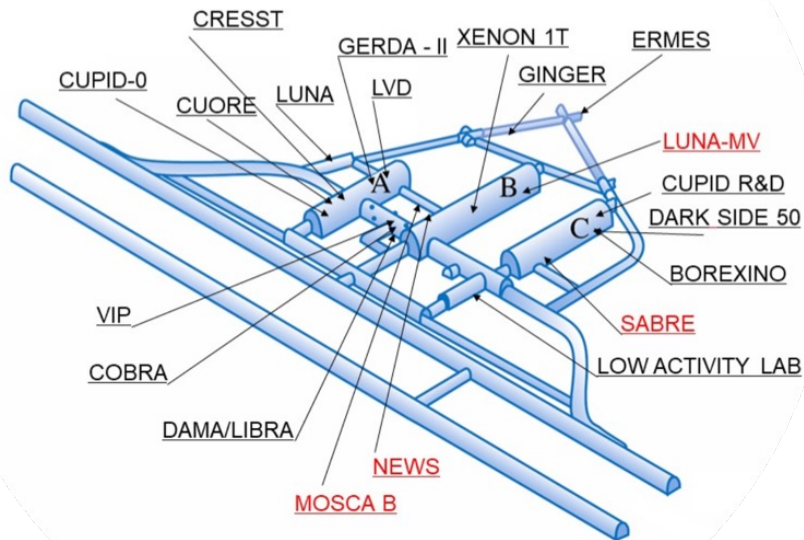
Julie Puputti

Jules Gascon

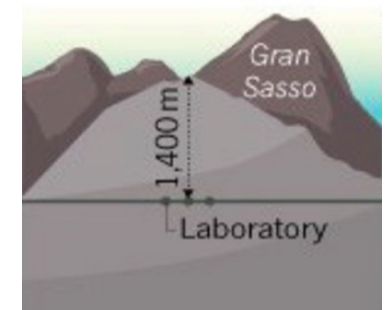
Carlos Peña Garay

LNGS / Gran Sasso Deep Underground Lab

- Shielded by 1400 m (3800 m.w.e.) of rock (Gran Sasso Mountains)
- Total Muon flux $3 \times 10^{-8} \text{ cm}^{-2} \text{ s}^{-1}$
- Radon $\sim 100 \text{ Bq/m}^3$ with 5-8 air changes/day
- 3 main experimental halls: 100 m long, 20 m width and 18 m height (Vol = $180,000 \text{ m}^3$)
- 22 experiments data taking or under construction
- Laboratory for very low radioactivity measurements

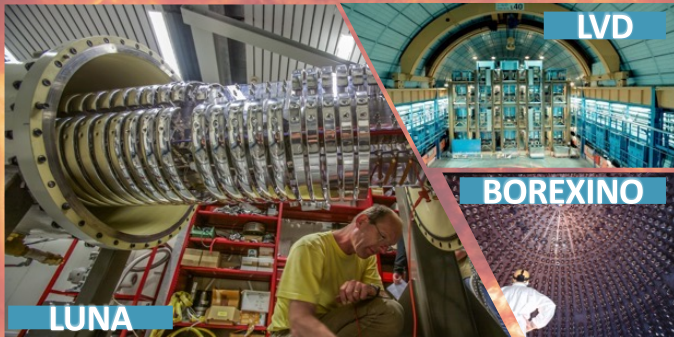


Area: **17.800 m²**
Volume: **180.000 m³**



Gran Sasso Science

Neutrino Astrophysics



Nuclear Astrophysics

Dark Matter Search

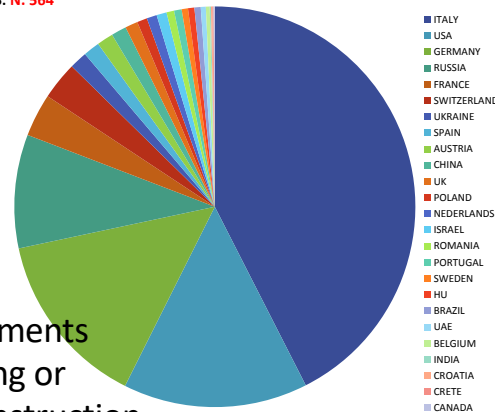


TAUP2021, 26 August – 3 September 2021

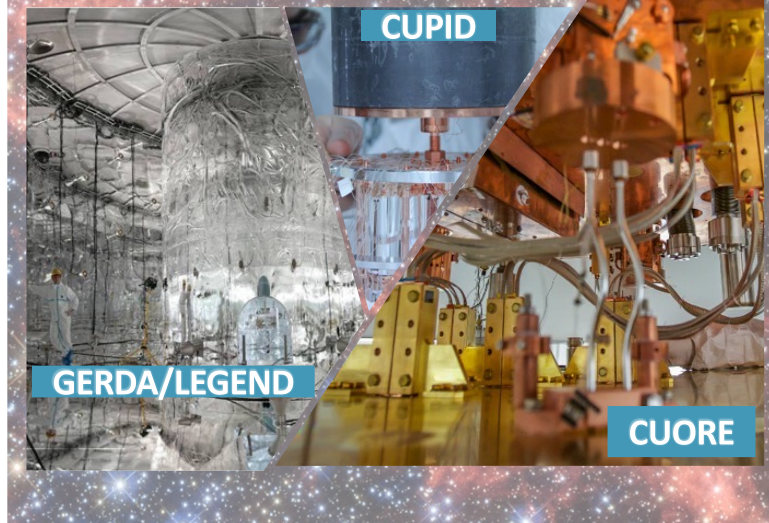


TOTAL USERS: N. 981
ITALIAN USERS: N. 417
FOREIGN USERS: N. 564

22 experiments
data-taking or
under construction



Neutrinoless Double Beta Decay



..... but also

- **Test on quantum mechanics**
 - Study on Planck invariance
 - Electron decay
- **Radiobiology**
 - Biological effects of low radioactive environment
- **Geophysics**
 - Earthquake monitoring and study
 - Analysis of water resources
- **Ultra Trace elemental analysis**
 - Low radioactivity tests and measurements
 - Cultural Heritage analysis
 - Advanced additive manufacturing

E. Previtali

Gran Sasso Status

Despite the pandemic outbreak:

Many experiments continue the data taking (Borexino, CUORE, etc.)

Some experiments continue the installation (XENON-nT, LEGEND-200)

LUNA-MV. Assembling. Commissioning scheduled in early 2022

LVD and Borexino decommissioning underway

Refurbishing of the underground spaces

Availability of existing infrastructures for new experiments

(inc **LEGEND-1000**, **G3-XeDM** etc)

New underground **Cryo test facility** for low temperature devices

Commissioning scheduled for late 2022

New **STELLAR facility for material screening** (16 HPGe, alpha counting, Liq scint).

ICP-MS facility scheduled for the beginning of 2022

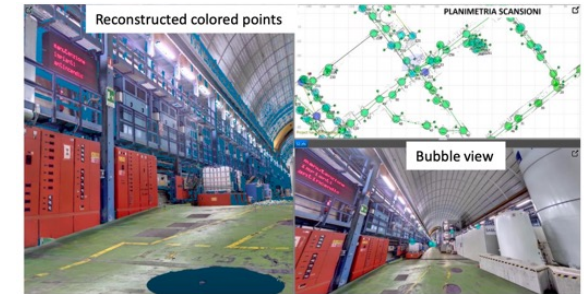
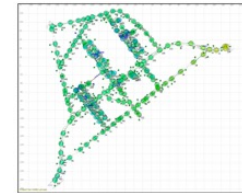
NOA ultra-clean facility for SiPM photosensors production, testing, packaging

Commissioning early 2022

Enlarging the lab workshop and of the 3D printing facility

A dedicated new underground workshop will be installed

Facility 3D-Scanning



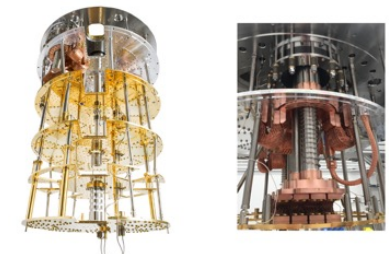
STELLA (SubTERRanean Low Level Assay)



High sensitivity ICP-MS.



NOA clean room assembly facility



Cryo-facility for testing of low temp devices

LSM Status & Plans



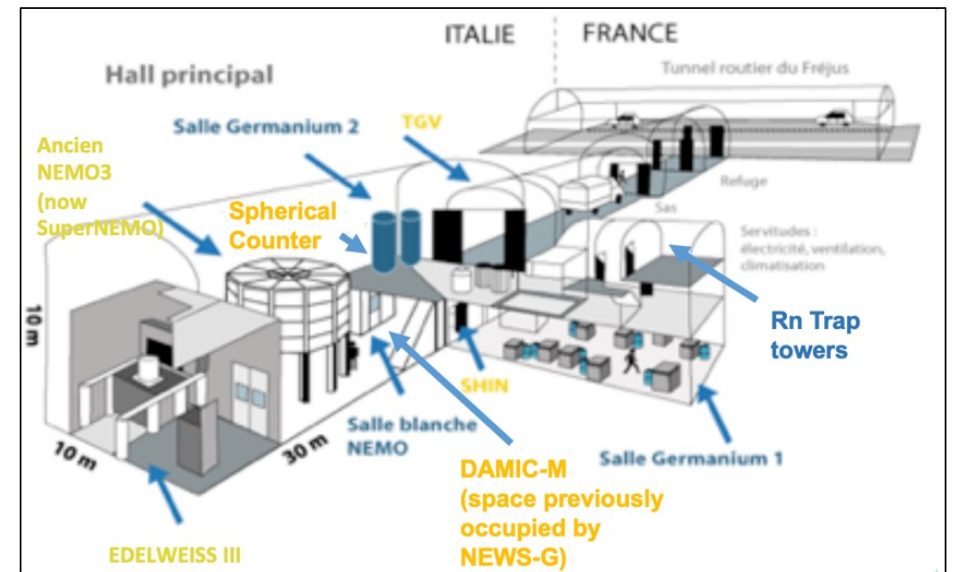
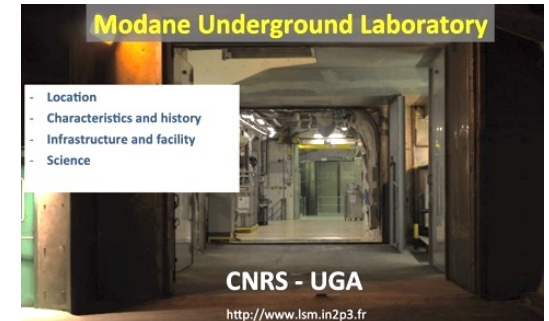
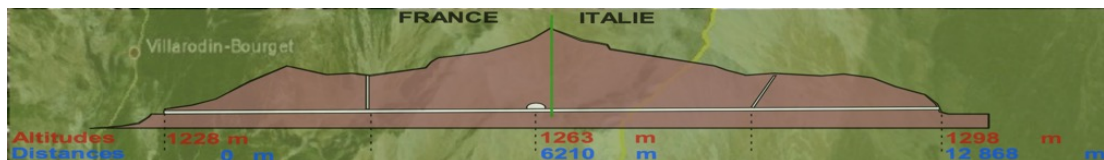
Laboratoire Souterrain de Modane (LSM)

- Depth: 4800 mwe
(Deepest UG Lab in EU)
- Volume: 3500 m³
- Radon: ~15 Bq/m³
- Access: Horizontal
- Staff: ~ 13
- Projects: 7-9



IN2P3
Les deux infinis

UGA
Université
Grenoble Alpes

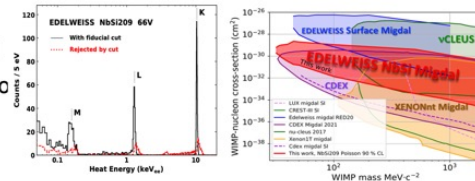


LSM current status and plans

Low-mass Dark Matter

Recent physics results:

- **EDELWEISS** [arXiv:2203.03993] Migdal limits for <35 MeV WIMPs with 200g Cryo with new NbSi TES phonon sensor

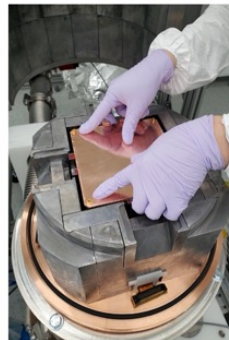
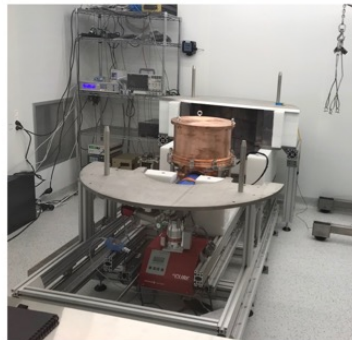


In preparation / coming results:

- **CRYOSEL**: Cryogenic Ge with single- e^- tag using μ -wire NbSi TES sensor: 40 g detector in BINGO cryostat @ LSM (2023)

- **DAMIC-M**: Search for low-mass Dark Matter with 1kg skipper CCDs

- Start of physics run with 2 CCDs (1 kg.d goal)

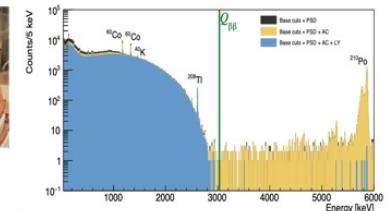
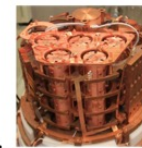


- Science program adapted to LSM size:
 - Low-mass Dark Matter Experiments
 - $0\nu\beta\beta$ demonstrators & technologies
 - HPGe array for low-radioactivity

$\beta\beta 0\nu$ demonstrators & technologies

Recent physics results:

- **CUPID-Mo** 20 x 0.2 kg scintillating Bolometers. Mo- 100 test, CUPID demo
- [arXiv:2202.08716] **New leading limits on ^{100}Mo $0\nu\beta\beta$ & beta decays**

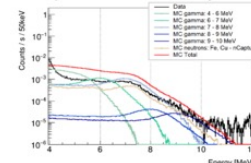


In preparation / coming results:

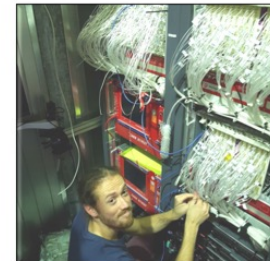
- **BINGO**: Development of next generation cryogenic $\beta\beta 0\nu$ technologies with reduced support mass, Neganov-Luke light detectors and active shield

- **SuperNEMO installation and commissioning**

LSM published ambient flux ($\gamma+n$) vs SuperNEMO calorimeter-only data



Tracko-Calorimeter detection of $bb0n$ decays with identification of the two electron tracks



LSM current status and plans

- 22 HPGe of various volumes
- Wide variety of tested sample :
- Assay of low radioactivity material
- Environmental studies: sediment cores, nuclear contamination monitoring
- 2β excited states

Detection limits for Germanium

Nuclide	Bq/kg
^{210}Pb	< 1,58E-02
^{226}Ra	< 1,27E-03
^{238}U	< 6,27E-03
^{228}Ra	< 3,82E-03
^{228}Th	< 8,66E-04
^{230}Th	< 1,42E-01

Planar detector



Limits for double beta decay of ^{58}Ni

Decay mode	Final state or Decay transition	$T_{1/2}$, (90% CL)
$\beta^+\text{EC}$	g.s.	1.7×10^{22} y
$\beta^+\text{EC}$	811 keV	2.3×10^{22} y
EC/EC	811 keV	3.3×10^{22} y
EC/EC	1675 keV	3.4×10^{22} y
$0\nu\text{EC/EC}$ resonant	Radiative 1918 keV	4.1×10^{22} y

Ongoing measurement: 6.5 kg of ^{82}Se



- Science program adapted to LSM size:
 - Low-mass Dark Matter Experiments
 - $0\nu\text{BB}$ demonstrators & technologies
 - HPGe array for low-radioactivity

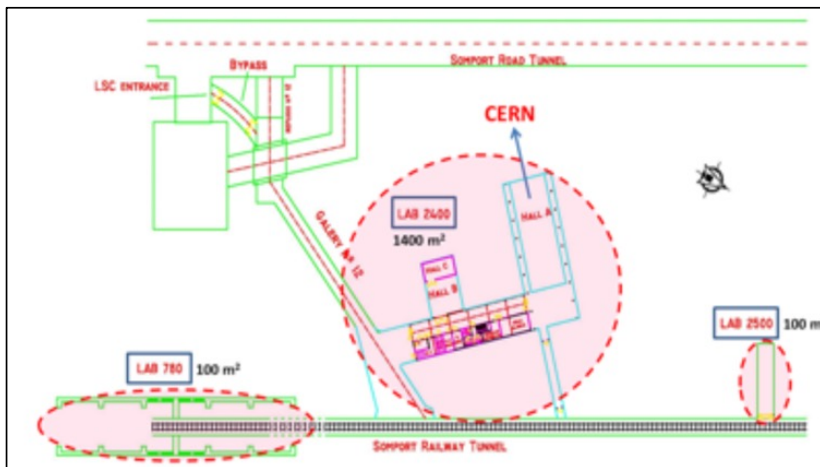
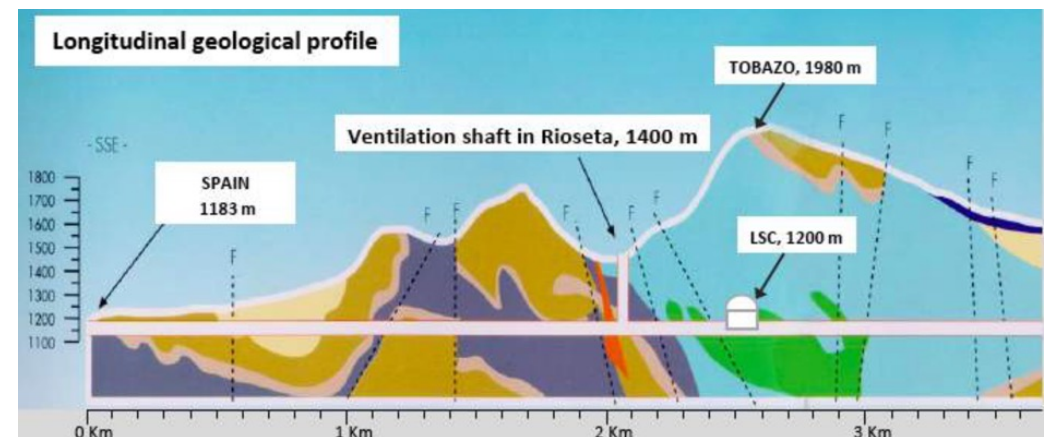


- PARTAGe: Detectors being merged into a common shield

Canfranc - LSC



- Depth: 2450 mwe
- Volume: 10,000 m³
- Radon: 50-80 Bq/m³
- Access: Horizontal
- Rail tunnel between France & Spain



1986 - First experiments in train tunnel
 2003-2006 - new lab built 1600m²
 2007-2010 - refurbishment works
 Since 2010 - re-start experimental activities
 Previous Directors: A. Bettini, A. Ianni

Inlet air flux: 20000 m³/h
 Radon: 50-80 Bq/m³
 Radon-free: 1 mBq/m³, 220 m³/h
 Muons: $(5.3 \pm 0.2) \cdot 10^{-3} \text{ m}^{-2}\text{s}^{-1}$
 Neutrons: $3.5 \cdot 10^{-6} \text{ cm}^{-2}\text{s}^{-1}$



Experiments

Neutrino physics

- **NEXT** – ^{136}Xe high-pressure gas TPC (data and construction)
- **CROSS** – Cryogenic Observatory with Surface Sensitivity for CUPID
- **SK-Gd & Hyper-K** – Screening and R&D (e.g., PMT covers)

Dark matter searches

- **ANAIS** – 112 kg NaI crystals (3-yrs data) to verify DAMA-LIBRA
- **DaRT** – Argon activation detector for DarkSide (GADMC)
- **TREX** – Nobel gas (Ne,Ar) high-pressure TPC

Lab Services

HP Ge detectors

Electroformed Cu facilities

Rn reduction ($220 \text{ m}^3/\text{h}$)

Rn monitoring ($1 \text{ mBq}/\text{m}^3$)

Rn-emanation detector





NEW LINE: BIOLOGY UNDERGROUND

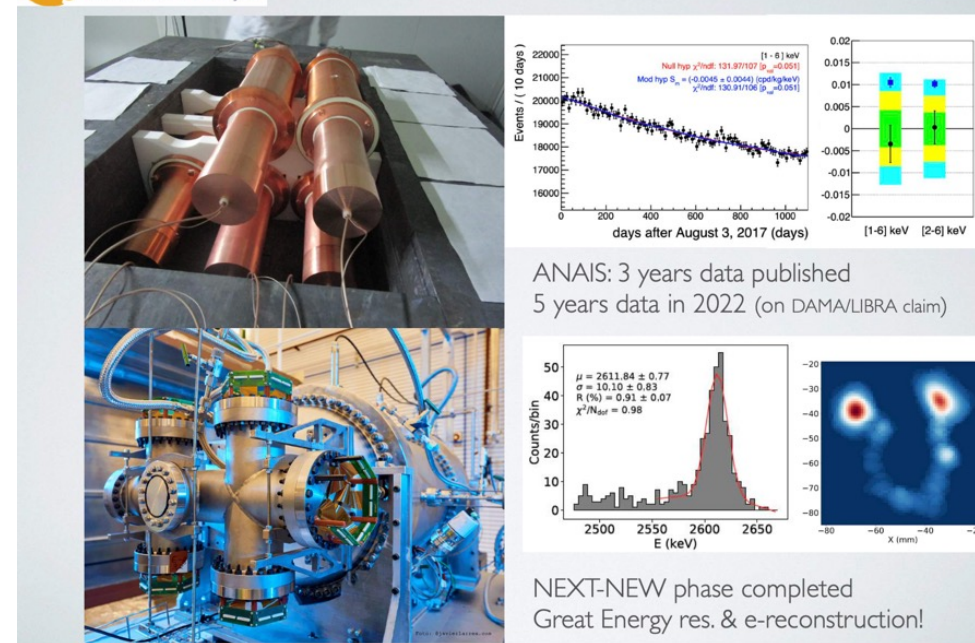
The Biogeochemistry, Biophysics, Radiobiology, and Technical Challenges of Deep Subsurface Research, 2021




New biolab underground. Explore suppression of DNA repair mechanisms. Expressions of Interest approved:

- Life in Heavy Water and its Energy Source [CBMSO] - Microorganisms in D_2O
- Darwinian evolution (De Luria-Delbruck) [I2SysBio] - E. Coli
- DNA Damage repair [UPF] - E. coli
- Multicellular Structure Formation [IBE] - S. Arctica, C. Owczarzak
- Interaction between host and pathogens [I2SysBio] - C. Elegans, O. Nodavirus

LSC MAIN SCIENCE RESULTS IN 2021



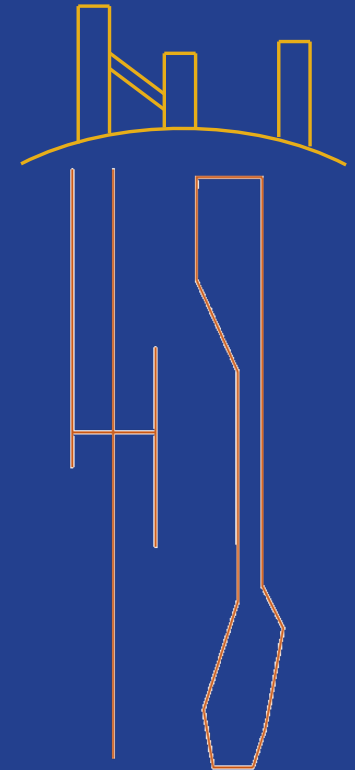
Future aims: NEXT: Ton-scale. Hyper-K construction, cryogenic technologies and misc. low background R&D.



CALLIO LAB

Underground Center for Science and R & D

Coordinator, Jari Joutsenvaara (jari.joutsenvaara@oulu.fi)
Project engineer, Julia Puputti (julia.puputti@oulu.fi)



CALLIO LAB

Underground Centre for Science and R&D

LOCATED AT THE 1.4 KM (4100 MWE) DEEP PYHÄSALMI MINE, PYHÄJÄRVI, FINLAND

UNIQUE UNDERGROUND RESEARCH NETWORK AND INFRASTRUCTURE - ACCESS, DEPTH, FACILITIES

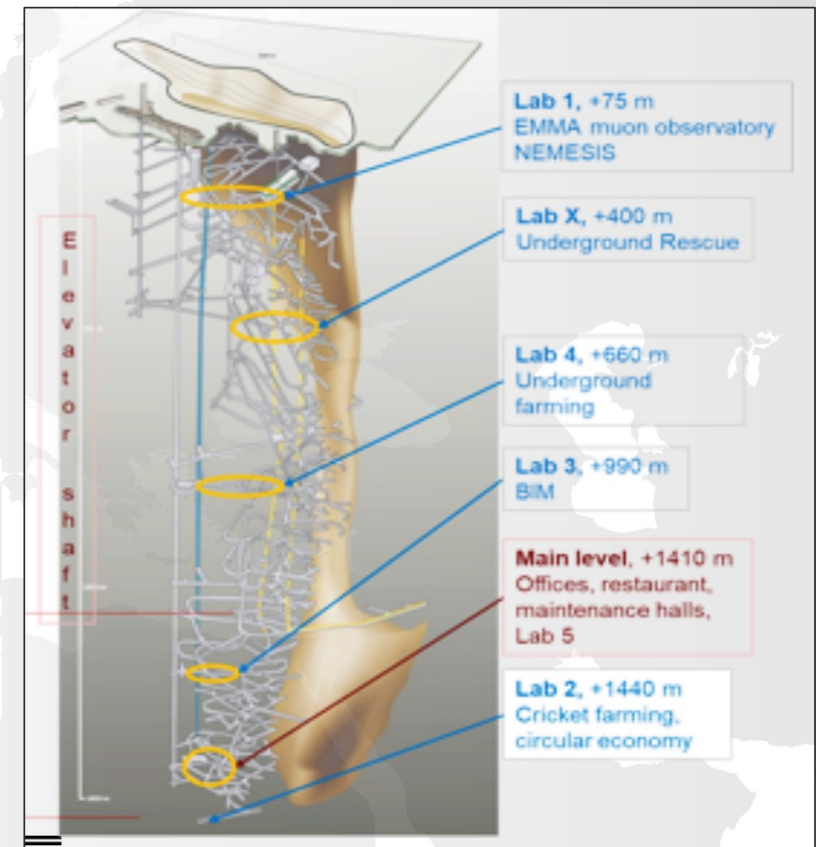
CURRENTLY SIX UNDERGROUND HALLS OR TUNNEL NETWORKS HAVE BEEN TURNED INTO MINE RE-USE FACILITIES: LABS.

MINING ENDS IN JUNE 2022. POST-MINING ACTIVITIES COORDINATED BY CALLIO PYHÄJÄRVI – BUSINESS CONCEPT

MULTI-DISCIPLINARY STEERING GROUP ESTABLISHED 2020



FACILITIES



CALLIO LAB

Underground Centre for Science and R&D

ACTIVITIES

- **EMMA:** Experiment with a MultiMuon Array, cosmic-ray induced bkgds using drift chambers
- **NEMESIS:** New Emma MEasurement with neutronS in cosmic Showers, study neutron bursts in shielding materials (also performed at other European labs)
- **C14:** Measure ¹⁴C isotope in oil-based liquid scintillators (goal of 10e-20 or lower)
- **BSUIN:** Member of the Baltic Sea Underground Innovation Network (13 partners from 8 countries), incl bkgd measurements, develop best practices, etc
- **Goldeneye:** Test site for remote sensing technology (safety and environmental monitoring)
- **Occupational Health:** Intelligent, adaptive lighting studies for UG workers
- Biology & food production, geology & hydrogeology
- UG Rescue & mining training



Coordinator, Jari Joutsenvaara
(jari.joutsenvaara@oulu.fi)

Project engineer, Julia Puputti
(julia.puputti@oulu.fi)

Future: Globally recognised underground research network and infrastructure



Education and training



Future food & Underground farming



Mining & tunnelling



SpaceLab



Mine reuse



Earth Observation and remote sensing



Geothermal research



Deep underground low background facility



Working environment



Particle physics & muography



Underground H&S



Something new?

Boulby Underground Laboratory (UK)

UKRI Science and Technology Facilities Council
Boulby Underground Laboratory



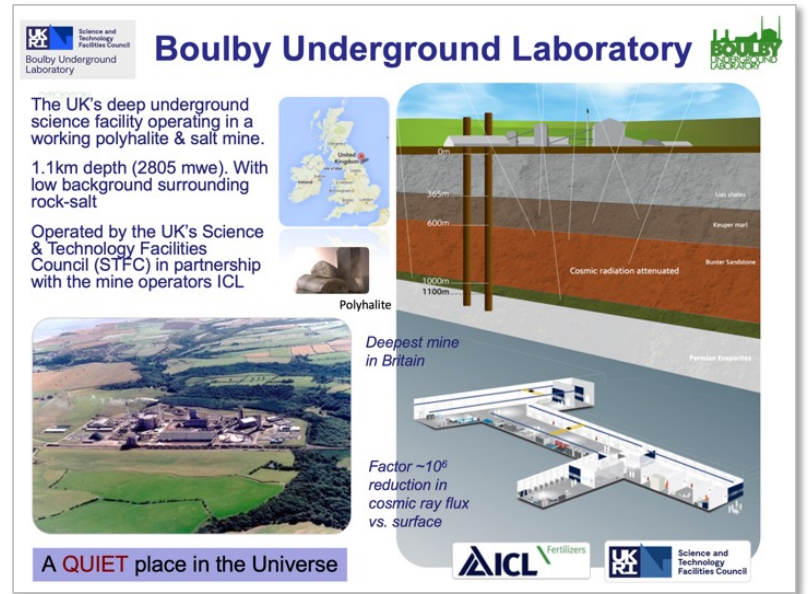
Office space, chemistry & clean prep lab, storage and staging space, IT room, conference room,

Surface support and staging building

3000m³ Outside Experimentation Area

Boulby Underground Lab Facilities 2020:
>4000m³ class 1k & 10k clean room lab space
100Mb Internet AC, Air filtration, 5T & 10T lifting, LN generation, fume hood & clean prep
3000m³ Outside Expt. Area. Power & internet

BUGS+ Material screening



Boulby Underground Laboratory

The UK's deep underground science facility operating in a working polyhalite & salt mine.

1.1km depth (2805 mwe). With low background surrounding rock-salt

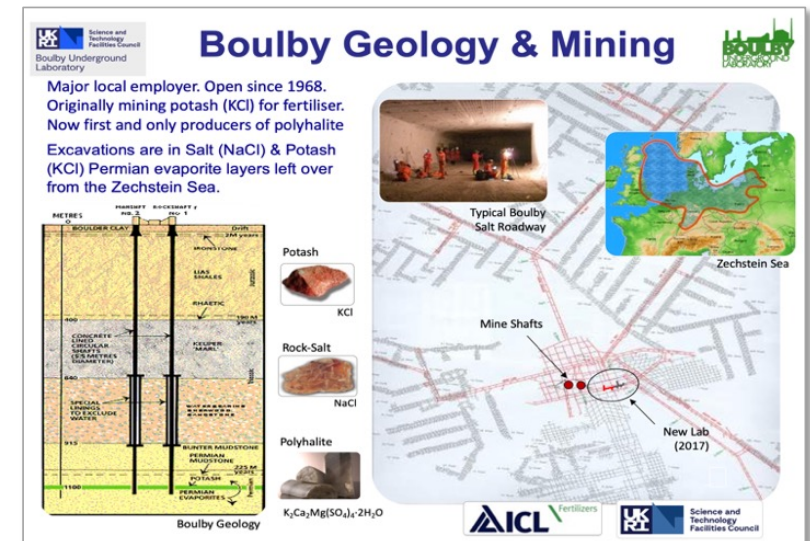
Operated by the UK's Science & Technology Facilities Council (STFC) in partnership with the mine operators ICL

Deepest mine in Britain

Factor ~10⁶ reduction in cosmic ray flux vs. surface

A QUIET place in the Universe

Logos: AICL, Fertilizers, UKRI, Science and Technology Facilities Council



Boulby Geology & Mining

Major local employer. Open since 1968. Originally mining potash (KCl) for fertiliser. Now first and only producers of polyhalite

Excavations are in Salt (NaCl) & Potash (KCl) Permian evaporite layers left over from the Zechstein Sea.

Logos: UKRI, Science and Technology Facilities Council, AICL, Fertilizers, UKRI, Science and Technology Facilities Council

Boulby Underground Laboratory (UK)



Boulby Facility Details...

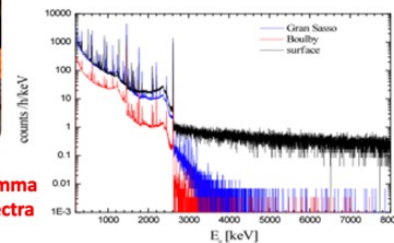
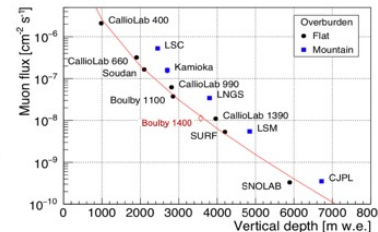


- The UK's deep underground science facility. One of 5 in Europe, <15 in the world.
- Supports work of >10 collaborative projects (astrophysics to climate, geology, environment etc), >40 institutions, >170 scientists & students.
- Facility funded and operated by the Science & Technology Facilities Council (STFC).
- Operations, H&S & science programme managed by 10 (+2) onsite staff and supported by Rutherford Appleton Lab (PPD).
- Mine operators ICL-UK provide wide-ranging operational & high level support.



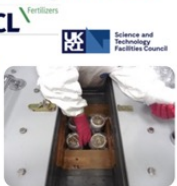
How does Boulby Compare?

- Low Radon levels (3 Bq/m³)
- Diverse science programme.
- Science and Industry partnership



Underground Science @ Boulby Mine

- DRIFT/CYGNUS: Directional Dark Matter
- Spherical Proportional Counters (NEWS-G) R&D
- BUGS: Ultra-low background material screening (for LUX-ZEPLIN and Super-K-Gd and more)
- AWE(Ge): Atmospheric gamma spectroscopy
- RESOURCE: Salt cavity energy storage study
- BISAL: Geo-microbiology / Astrobiology studies
- MINAR: Space Exploration Tech. Development
- Misc. Low Background & Geoscience...
- Etc... (More to come).



Astrobiology & planetary exploration

A busy & growing multi-disciplinary science programme:
Astrophysics and Low Background science, Earth and Environmental Science, Astrobiology and Planetary Exploration.



Boulby Science Now & Future

Particle physics and ultra-low background studies

BUGS

XIA alpha particle counter
 <0.0001 alphas/cm²/hr

8 ULB Ge detector systems, 2 XIA alpha counters, Rn emanation, ICPMS to come

BUGS (Boulby UnderGround Screening). World-class material screening for current and future ULB experiments. Towards PPT sensitivity for G3 DM and Neutrino experiments

LZ PMTs

Aiming for ALL key ULB screening systems under one (1.1km) roof.

(XinRan Liu, this conf.)

Boulby Dark Matter Studies...

Boulby has hosted **Dark Matter** search studies for over two decades. Including the **NAIAD**, **DRIFT** & **ZEPLIN** experiment programmes.

Boulby now hosts **CYGNUS** directional DM programme, **NEWS-G**/Dark-Sphere R&D and providing ULB material screening for other studies, inc **LUX-ZEPLIN (LZ)**

Galactic rotation curves

ZEPLIN-II & III:
 The world's first 2-phase Xenon dark matter detectors (Finished 2011)

World DM particle search limits and future projections

ZEPLIN-III @ Boulby

NEWS-G

Spherical Proportional Counter (SPC) studies @ Boulby

k. Nikolopoulos, I. Katsioulas, P. Knights, T. Need, R. Ward, University of Birmingham And wider NEWS-G Collab.

SPC concept: Variable target, Low E_{th} , Low mass sensitivity

Simulation study of neutron interactions in the S30 at Boulby

Purpose-made gas filter
 Copper Oxide, H₂O removal, Molecular sieve, O₂ removal

11-anode sensor

Al-S30 R&D Detector

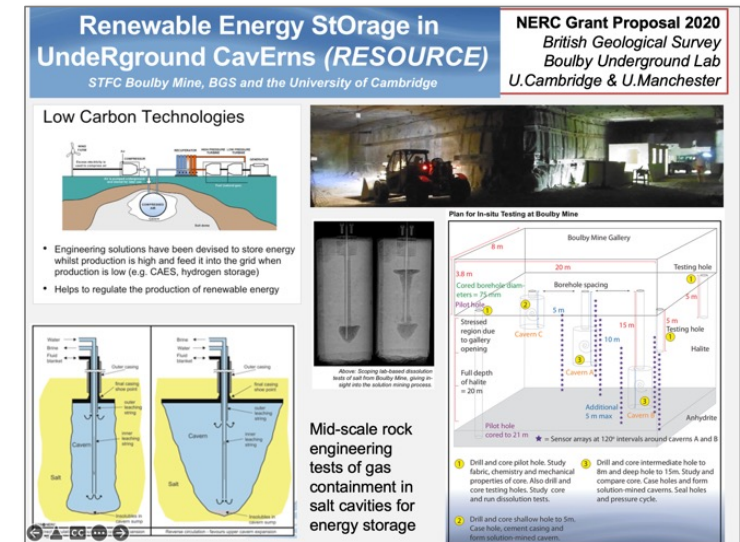
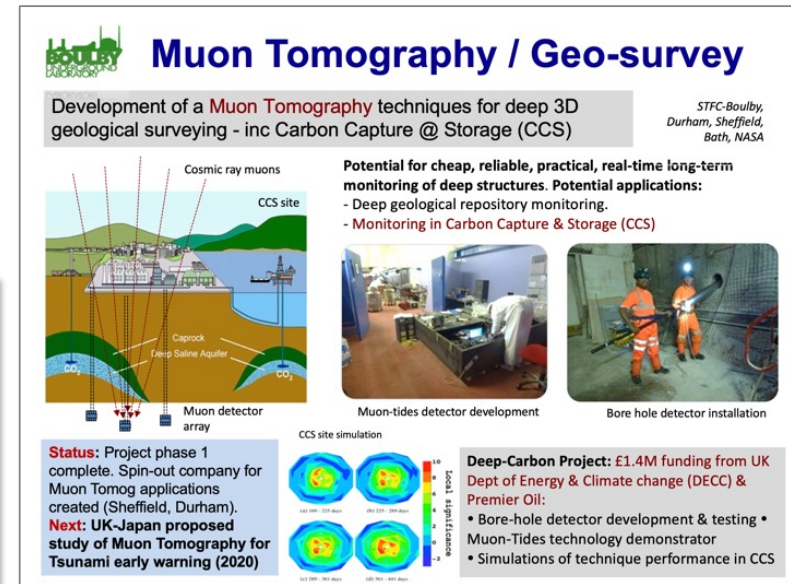
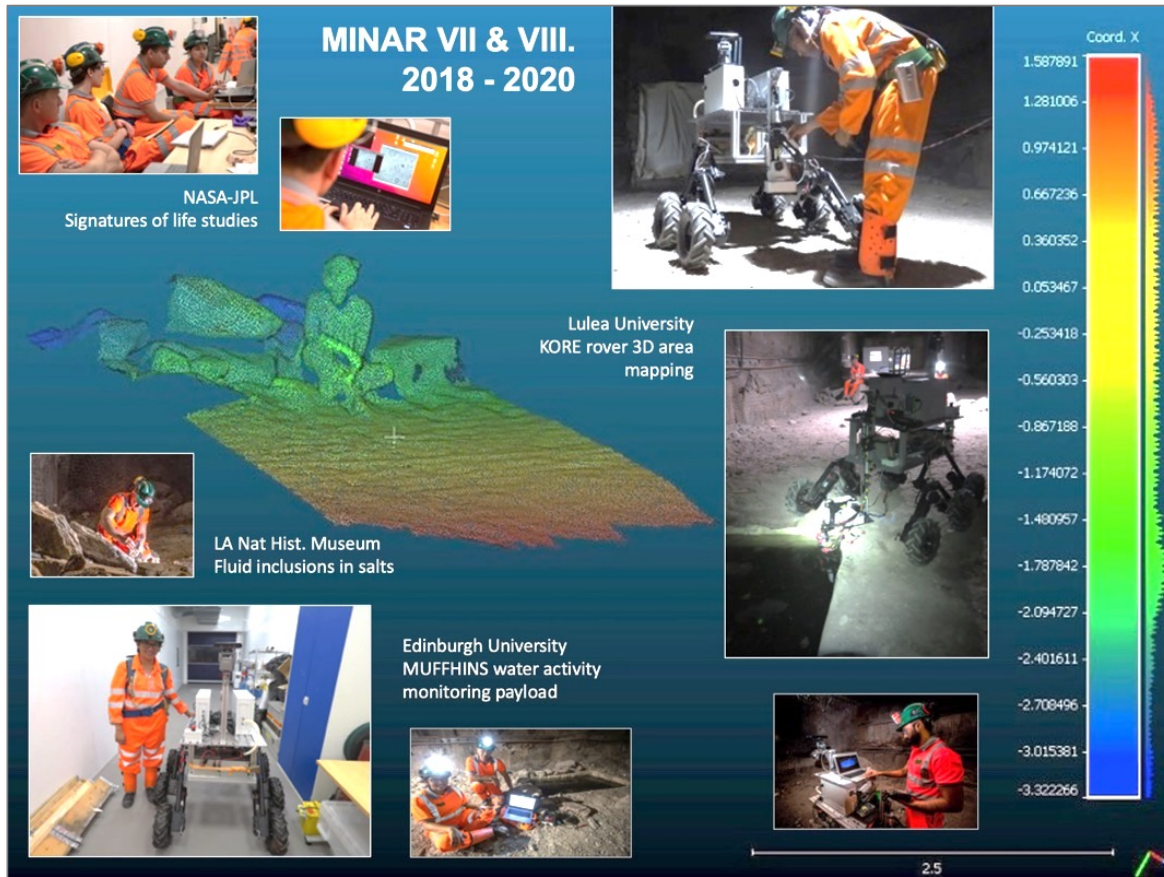
SPC Sensitivities

Direction of R&D at Boulby

- Instrumentation development alongside NEWS-G at SNOLAB
 - Multi-anode sensor
 - Gas mixtures & filtration
- Working towards scaled-up detector at Boulby, 3m diam. **DarkSPHERE**
- Establishing **Electro-forming Capability** at Boulby for Dark SPHERE and beyond
 (I. Katsioulas, This conf.)

Multi-disciplinary Science

Earth and environmental studies, low background and/or underground particle physics, Astrobiology & Planetary exploration.



Expanding Facilities & Science

Next Generation Rare Event Studies @ Boulby

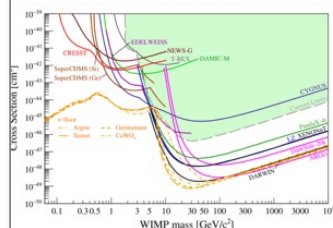
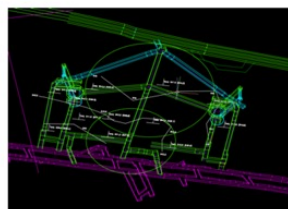
Towards EXPANDING Boulby to host MAJOR international Dark Matter, neutrino & fundamental science projects from 2030+



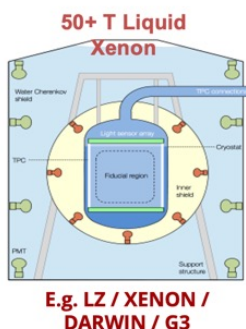
LZ, SURF, USA



Boulby-FS study:
Infrastructure design, feasibility & costing studies for next generation Dark Matter and/or 0vBB detectors
Study undertaken 2020-2021



Next generation DM and/or 0vBB at Boulby?



E.g. LZ / XENON / DARWIN / G3

Expansion bringing to the UK:

- **HIGH-impact, world-leading science**
- **BIG fundamental science questions**
- **LARGE multi-national collaborations**
- **MAJOR local & national investment, impact and visibility**

There is motivation, opportunity, support to grow...

Boulby Feasibility Study (Boulby-FS)

Submitted to STFC June 2021

FINAL REPORT

FEASIBILITY STUDY
FOR DEVELOPING THE BOULBY UNDERGROUND LABORATORY
INTO A FACILITY FOR FUTURE MAJOR
INTERNATIONAL PROJECTS

Supported by the STFC Opportunities Call 2019

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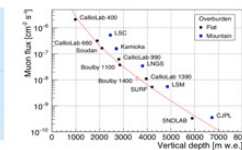
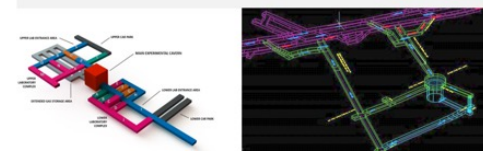
June 25, 2021

Issue v1.0

OFFICIAL SENSITIVE [COMMERCIAL]

Boulby-FS Study Overview:

- Context and need: Dark Matter (DM), Neutrinoless Double Beta Decay (0vBB)
- Infrastructure specifications for potential projects (LXe & LAr DM, Ge 0vBB, and more).
- Conceptual designs for excavations and outfitted labs – in 1.1km (Salt) and 1.4km (Polyhalite) layers
- Staffing and surface facility needs.
- Detailed costs and schedules.



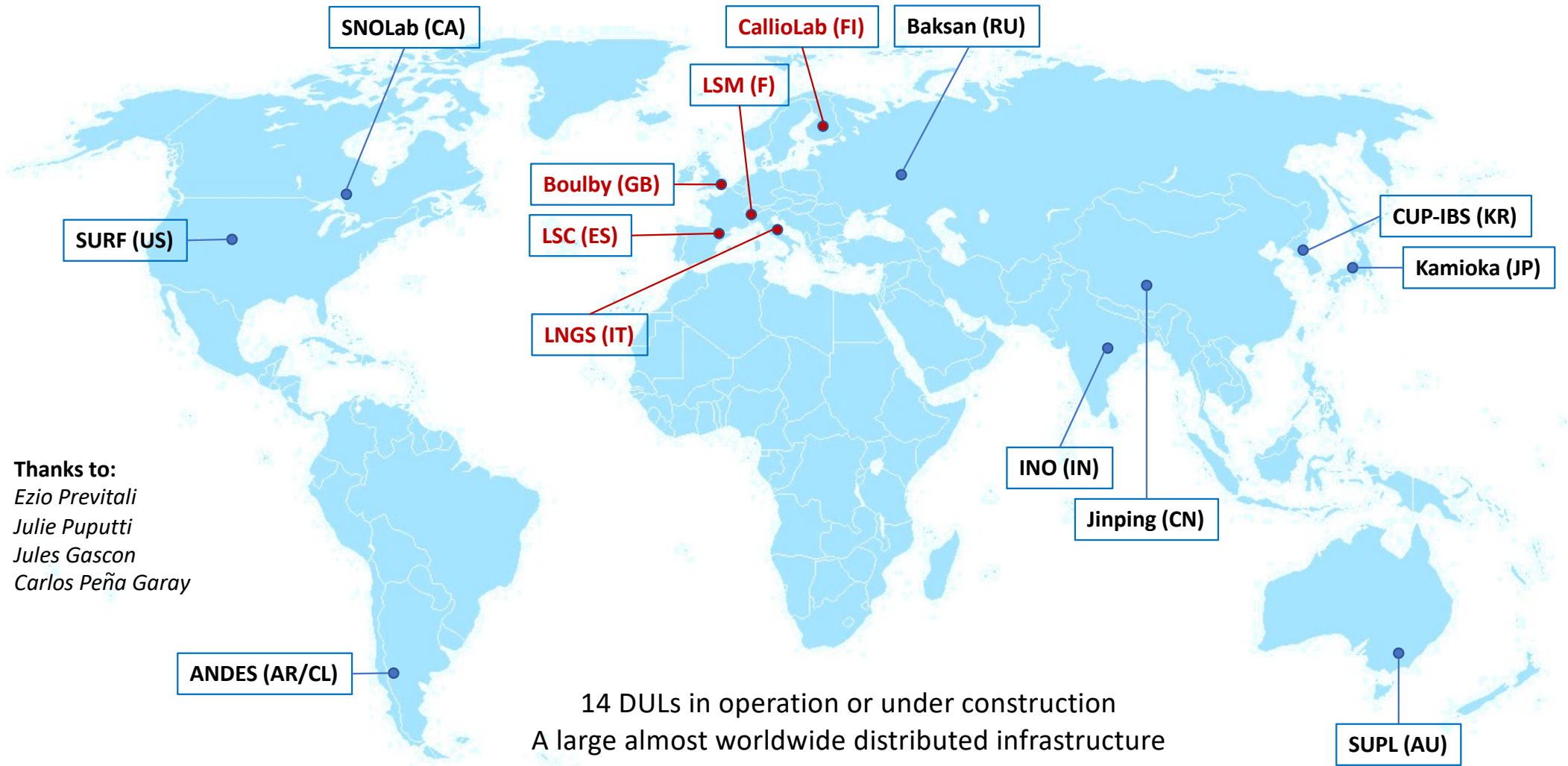
Government 'fit': Levelling Up, Strength in Places, Build Back Better

Results: It IS feasible, well motivated and timely.
Outfitted facility: £100m+ (Inc contingency, VAT)

A major new UK multi-disciplinary facility...

- Funding approved for next level designs at 1.1km and 1.4km depth options.
- A ~30,000m³ clean facility with >25m diam. main chamber plus ancillary rooms/spaces
- Strongly support by STFC and the mine operators ICL-UK.

World Deep Underground Science Labs



Overview of European Deep Underground Science Facilities

Summary

- A busy and exciting time in the international underground laboratory world.
- Many interesting and major experiments now operating, under construction or planned.
- Europe has a number of important, historic and diverse underground facilities. Some exciting and ambitious plans for the future.
- There are initiatives being progressed to combine the knowledge, capabilities and efforts of the EU underground labs – sharing experience of lab operation, potentially coordinating users' needs, joint development of underground science techniques.

APOGEIA proposal submitted to HORIZON-Europe call March 2022 (LNGS, Boulby, LSC, LSM, Calliolab, LSBB et. al.)

Sean Paling
STFC Boulby Underground Laboratory=

Europe then beyond?